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Towards this end, we have fabricated some small, a few millimeters in diameter, piezoelectric motors using ferroelectric thin films. These motors consist of two pieces: a stator and a rotor. The stationary stator includes a piezoelectric film in which we induce bending in the form of a traveling wave. Anything which sits atop the stator is propelled by the wave. A small glass lens placed upon the stator becomes the spinning rotor.

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AI Memo 1269 February, 1991

Piezoelectric Micromotors for Microrobots

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Abstract

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1 Smaller and Smaller

Robots today are large, expensive and not too clever. Robots of the future may be small and cheap (and perhaps still not too clever). But if we could achieve even insect level intelligence while scaling down sizes and costs, there may be tremendous opportunities for creating useful robots. From autonomous sensors to robots cheap enough to throw away when they have completed their task - microrobots provide a new way of thinking about robotics.

Our goal of building gnat-sized robots has been driven by recent successes in developing intelligence architectures for mobile robots which can be compiled efficiently into parallel networks on silicon. Brooks' subsumption-style architectures [**Brooks 86**] provide a way of combining distributed real time control with sensor-triggered behaviors to produce a variety of robots exhibiting "insect level" intelligence [**Brooks 89**], [**Angle 89**], [**Connell 90**], [**Mataric 90**], [**Flynn, Brooks, Wells and Barrett 89**], [**Maes and Brooks 90**]. This assemblage of artificial creatures includes soda can collecting robots, sonar-guided explorers, six-legged arthropods that learn to walk and a "bug" which hides in the dark and moves towards noises.

One of the most interesting aspects of the subsumption architecture has to do with the way it handles *sensor fusion*, the issue of combining information from various, possibly conflicting, sensors. Typically, sensor data is fused into a global data structure and robot actions are planned accordingly. A subsumption architecture however, instead of making explicit judgements about sensor validity, encapsulates a strategy which might be termed *sensor fission*, whereby sensors are only dealt with implicitly in that they activate behaviors. Behaviors are just layers of control systems which all run in parallel whenever appropriate sensors fire. The problem of conflicting sensor data then is handed off to the problem of conflicting behaviors. "Fusion" consequently is performed at the output of behaviors (*behavior fusion*) rather than the output of sensors. A prioritized arbitration scheme then selects the dominant behavior for a given scenario.

The ramification of this distributed approach to handling vast quantities of sensor data is that it takes far less computational hardware. Since there is no need to handle the complexities of maintaining and updating a map of the environment, the resulting control system becomes very lean and elegant.

The original idea for gnat robots [**Flynn 87**] came about when this realization that subsumption architectures could compile straightforwardly to gates coincided with a proposal by [**Bart, Lober, Howe, Lang and Schlect 88**] to fabricate an electrostatic motor on a chip (approximately 100-μm in diameter). Early calculations for this silicon micromotor forecast small but useful amounts of power. Already, many types of sensors (i.e. imaging sensors, infrared sensors,

force sensors) microfabricated on silicon are commercially available. If a suitable power supply could be obtained (solar cells are silicon and thin film batteries are beginning to appear in research laboratories), the pieces might begin to fit.

The driving vision is to develop a technology where complete machines can be fabricated in a single process, alleviating the need for connectors and wiring harnesses and the necessity for acquiring components from a variety of vendors as would be found in a traditional large-scale robot. The microrobots would be designed in software through a "robot compiler" and a foundry would convert the files to masks and then print the robots en masse. One critical technology presently missing is a batch-fabricatable micromotor which can couple useful power out to a load.

Various types of intriguing microactuators have recently appeared such as variable capacitance silicon electrostatic motors (which are based on the force created due to charge attraction as two plates move past each other) **[Tai, Fan and Muller 89]**, **[Fujita, Omodaka, Sakata and Hatazawa 89]**, **[Mehregany, Bart, Tavrow, Lang and Senturia 90]**. Figure 1 illustrates one such electrostatic micromotor. Another type of micromotor is a "wobble" motor, where one cylinder precesses inside another, again due to electrostatic forces **[Jacobsen, Price, Wood, Rytting and Rafaelof 89]**, **[Trimmer and Jebens 89]**. Figure 2 illustrates a wobble motor. In general, electrostatic motors are preferred over magnetostatic motors in the microworld because electrostatic forces scale favorably as dimensions shrink and because dielectric materials are more easily patterned and processed than magnetic materials, especially in the realm of silicon processing. The three-dimensional windings required for magnetostatic motors would be very hard to fabricate in silicon, but the small gap sizes that allow electrostatic motors to take advantage of the ability to withstand increased electric fields before breakdown are easily fabricated using photolithographic techniques. Electrostatic micromotors however have demonstrated successes but also uncovered limitations. Problems with these types of motors arise in the areas of friction, fabrication aspect ratio constraints and low torque to speed characteristics.

[Flynn, Brooks and Tavrow 89] provides a detailed summary of these problems and proposes a piezoelectric ultrasonic micromotor as an alternative approach. This structure, fabricated from thin-film lead zirconium titanate (PZT), circumvents many of the drawbacks of electrostatic micromotors. This paper reports on our experiences with the first prototype motors that we have fabricated.

Our idea is based on the underlying principles of commercially available ultrasonic motors presently popular in Japan **[Inaba, Tokushima, Kawaski, Ise and Yoneno 87]**, **[Akiyama 87]**, **[Shinsei 88]** and **[Kumada 90]** which essentially convert electrical power to mechanical power through a piezoelectric interaction. Mechanical power is then coupled to a load through a frictional phe-

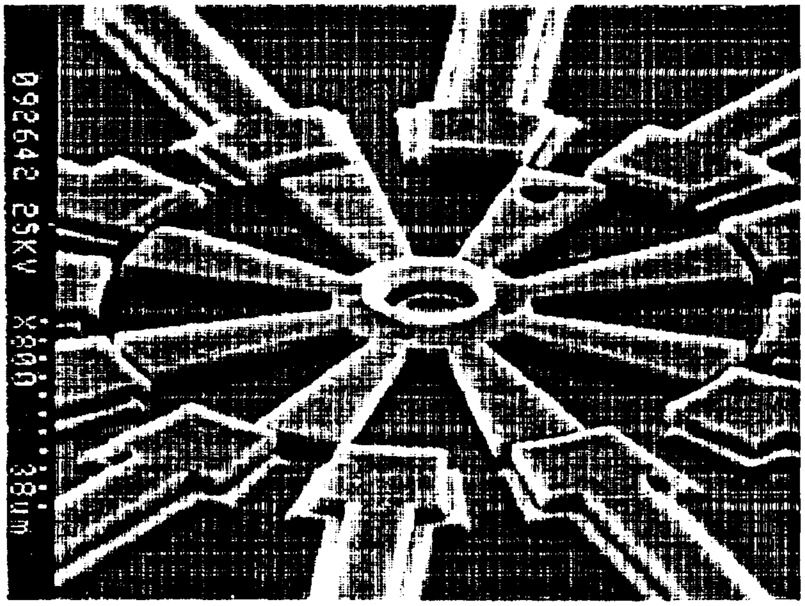

Figure 1: A variable capacitance motor has a 100-μm diameter rotor which revolves around a bearing as oppositely placed stators are sequentially stepped with the applied drive voltages [**Tavrow 91**].

nomenon induced by a traveling wave deformation of the material. Piezoelectric motors display distinct advantages over traditional electromagnetic motors such as small size, low noise, and high torque to speed ratios. These commercially available motors however, use PZT in its bulk ceramic form, which must be cut and milled.

Our contribution has been to realize that if PZT can be deposited in a thin film form compatible with silicon processing, then motors can be manufactured in a batch printing process instead of being individually machined.

Additionally, these motors should show significant improvements in performance over bulk PZT motors. That is, because the films are very thin, it is possible to apply much higher electric fields than in thicker bulk devices. This leads to higher energy densities.

2 Advantages of Piezoelectric Motors

Energy Density – The baseline argument for pursuing piezoelectric ultrasonic

Figure 2: The wobble motor contains a rotor which is attracted to active electrodes as the drive voltages are sequenced around the perimeter, similar to a variable capacitance motor. Since the rotor is the bearing, it tends to "wobble" **[Jacobsen et al. 89]**.

micromotors is based on energy density considerations. The maximum energy density storeable in the air gap of an electrostatic micromotor is

$$\frac{1}{2}\epsilon_{air}E_{bd}^2$$

where E_{bd} is the maximum electric field before breakdown (approximately $10^8\frac{V}{m}$ for 1-μm gaps) and where ϵ_{air} is the permittivity of air (equal to that of free space).

For a piezoelectric motor made from a ferroelectric material such as PZT, the energy density becomes

$$\frac{1}{2}\epsilon_{pzt}E_{bd}^2$$

Thin film PZT can similarly withstand high electric fields ($E_{bd} \cong 10^8\frac{V}{m}$), but the dielectric constant is three orders of magnitude larger ($\epsilon_{pzt} \cong 1300\epsilon_0$) larger than air. Other types of thin film piezoelectric (but not ferroelectric) ultrasonic actuators have been produced **[Moroney, White and Howe 89]** from zinc oxide, but the dielectric constant is only one order of magnitude larger ($\epsilon_{zo} \cong 10\epsilon_0$) than air. The greater the energy density stored in the gap, the greater the potential for converting to larger torques, or useful work out.

Low Voltages – Piezoelectric motors are not required to support an air gap. Mechanical forces instead, are generated by applying a voltage directly across the piezoelectric film. Because these ferroelectric films are very thin (ours are typically 0.3-μm), intense electric fields can be established with fairly low voltages. Consequently, we drive our thin film PZT motors with two to three volts

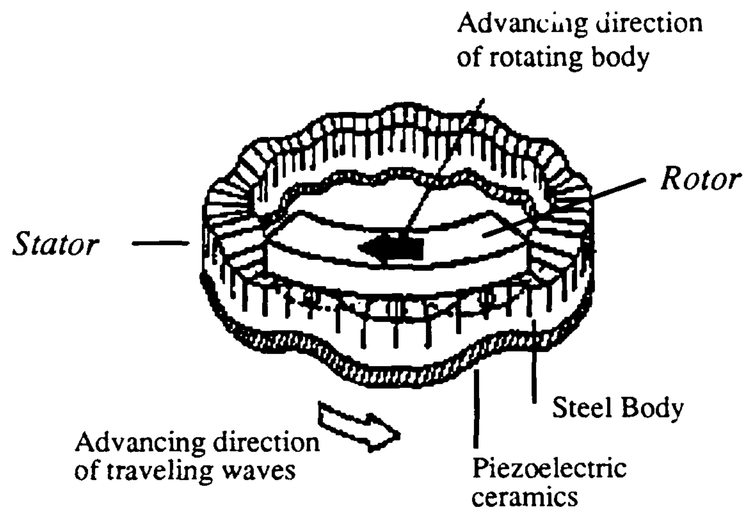

Figure 3: An electrically induced wave of mechanical deformation travels through a piezoelectric medium in the stator of an ultrasonic motor **[Panasonic]**.

as opposed to the hundred or so volts needed in air-gap electrostatic actuators.

Geardown – Energy density comparisons may be the primary motivators in pursuing PZT micromotors, but there are other advantages as well. Because this strong dielectric material also *bends* with applied voltage, mechanical power can be coupled out in unique ways. Figure 3 illustrates an ultrasonic traveling wave motor marketed by Matsushita (Panasonic). Two bulk ceramic layers of PZT are placed atop one another. Each layer is segmented such that neighboring segments are alternately poled. That is, for a given polarity of applied voltage, one segment contracts while its neighbor expands. These two layers are placed atop one another but offset so that they are spatially out of phase. When also driven temporally out of phase, the two piezo layers induce a traveling wave of bending in the elastic body. Any point on the surface of the stator then moves in an ellipse and by contacting a rotor onto the stator, the rotor is pulled along through frictional coupling. Fast vibratory vertical motions are transformed into a slower macroscopic motion tangential to the surface where peak performance is attained at resonance. This geardown means that we can fabricate motors without the need for gearboxes. This is especially important when we compare to electrostatic variable capacitance micromotors which spin at tens of thousands

of revolutions per minute [**Bart, Mehregany, Tavrow, Lang and Senturia 90**]. Gearing down to a useful speed for a robot from such a motor would require a gear several feet in diameter. While electrostatic wobble micromotors are also able to produce an inherent gear reduction, they do not incorporate the advantage of high dielectric materials which the piezoelectric motors possess.

No Levitation – Friction is another major player in problems besetting micromotors. In a variable capacitance electrostatic micromotor, frictionless bearings are something to strive for, as the rotor needs to slide around the bearing. Piezoelectric traveling wave motors on the other hand, are based on friction – it is sliding that we we need to prevent. Consequently, there is no need to levitate the rotor, a fact which makes a piezoelectric motor much more amenable to designs for transmitting power to a load. Furthermore because the rotor in an electrostatic variable capacitance micromotor flies above the stator, it needs to be very flat. Electrostatic micromotors are small, on the order of 100-μm in diameter, because of the difficulties in fabricating large rotors without warpage. In a piezoelectric ultrasonic motor, the rotor is in physical contact with the stator, so the actuator can scale to much larger sizes for resulting higher torques.

Axial Coupling – The consequences of the effects of friction and stability in various types of micromotors force specific geometries on these actuators. Variable capacitance motors require a radial gap design due to stability considerations. That is, the capacitor plates sliding past each other are radially distributed about the bearing. Since silicon processing techniques cannot create large structures in the vertical dimension, that leaves very little area for energy transduction. Similarly, the physics of wobble motors constrains them to have cylindrical coaxial geometries. Ultrasonic motors however, due to this frictional coupling, can be formed into either linear or rotary motors and in addition, have the advantage that the rotor can sit atop the stator, creating more area over which to couple power out. The large planar area of ultrasonic motors is also symbiotic with planar lithographic techniques.

Rotor Material – Friction coupling (as opposed to charge attraction) leads to another trait characteristic of piezoelectric ultrasonic motors - the rotor can be any material. That is, the rotor need not be a good conductor as in variable capacitance or wobble motors. Rotor conductivity is unimportant, in contrast to an electrostatic induction micromotor. *Most importantly*, a piezoelectric ultrasonic motor could actuate a pump, and the fluid can then be *any* solution, without regard to conductivity.

Holding Torque – Finally, in terms of complete systems such as autonomous robots or battery operated machines, total energy consumption over the lifespan of the system is of critical concern. Piezoelectric ultrasonic motors, again due to friction coupling, can maintain holding torque even in the absence of applied power. This is a unique trait for an actuator that does not contain a gearbox.

much less a transmission system or a brake.

3 From Materials to Devices

Bulk ceramic PZT has been widely used for decades but thin film ferroelectrics are new arrivals, having only recently been developed for non-volatile memory applications [**Ramtron 88**], [**Udayakumar, Chen, Krupanidhi and Cross 90**]. One problem with these new ferroelectric memories is fatigue, as the chips actually *flex* when memory cells switch. But that is exactly the effect we seek to exploit!

We would like films that maximize the piezoelectric effect in order to design useful high torque, low speed micromotors but the leap from materials to devices is a large one. Standing on the shoulders of previous technology is, in general, a good idea (and one which has been the approach in electrostatic micromotor research to this point - some even going so far as to label them "IC-processed micromotors" [**Tai, Fan and Muller 89**]). Stepping away from known silicon processing techniques and incorporating a new material can be a large undertaking, especially when the aim is to develop a new device. Consequently, the design for the device has to be as simple as possible in terms of materials processing to ensure a reasonable chance of success.[1]

3.1 Keeping Things Simple

Figures 4 and 5 illustrate our initial designs for the stators of linear and rotary motors (carriages and rotors have not been microfabricated - at the moment we simply place small glass lenses or other materials down on the stators). A silicon-rich nitride layer is deposited on a silicon wafer and is then patterned on the backside to create a membrane. 120 stator structures are patterned per two-inch wafer. After the membranes are etched, piezoelectric capacitor structures are built. These structures consist first, of a bottom electrode formed from titanium and platinum. The PZT dielectric is then added and finally the patterned gold top electrodes are deposited. The bottom electrode and thin film PZT are laid uniformly over the entire wafer, while gold top electrodes are positioned only above membranes.

A close-up of the membrane cross section is shown in figure 6. Note that the silicon wafer and the silicon nitride membrane provide only structural support for the stator. No electrical properties or charge attraction effects of silicon

[1] Experienced designers usually note however, that the first way you design something is always the most complex way [**Angle 90**].

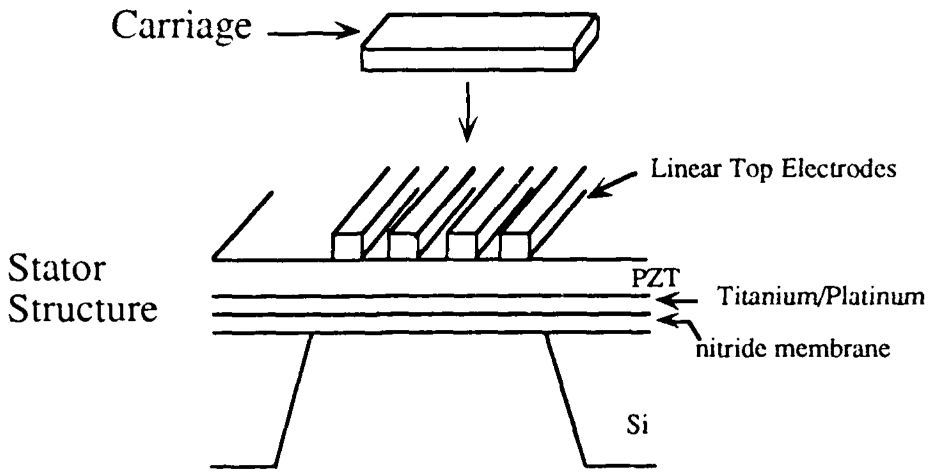

Figure 4: Linear motors utilizing thin-film PZT are illustrated here. By etching a membrane into a silicon wafer and patterning the stator on the membrane, the stator will be able to deflect more than if it were trying to bend the entire thickness of the wafer. Silicon-rich nitride is used for the membrane. The stator consists of a bottom electrode of titanium and platinum (ground), the PZT film and the patterned gold top electrodes. A carriage would have to be placed down by hand.

are presently used in this motor. Future iterations might find other manufacturing technologies more attractive, but for the present we use silicon for its accompanying tools and lithographic techniques.

These stators were designed in this fashion because the materials requirements here are much simpler than in, for instance, a Matsushita motor (figure 3, which would require two layers of ceramics with alternately poled segments throughout each piece. Our microfabricated stators require only one layer of PZT and that layer is poled uniformly everywhere. The tradeoff is that our motors now require a four-phase drive to induce a traveling wave, whereas the Matsushita motor requires only two phases. Patterning and wiring is very easy with photolithography. However, while multilayer materials with various geometries of poling are easily realized in macro scale assembled motors, these steps would be very cumbersome from a microfabrication point of view.

A more recent design is even simpler. We start with thinned wafers which are 75-μm thick (as opposed to the usual 250-μm) and omit membranes entirely. Since stress-free nitride is no longer required as an etch stop to create the membranes,

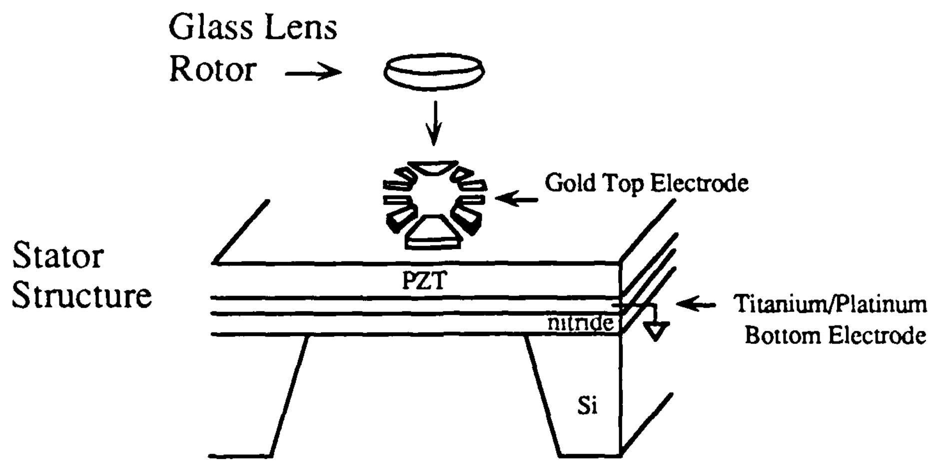

Figure 5: A rotary motor is made in the same way except that the top electrodes are patterned in a circle. We typically place down a small glass lens for a rotor.

the entire layer sequence just becomes silicon, oxide, Ti-Pt, PZT and then gold (titanium is required for adhesion reasons and oxide is necessary to separate silicon from reacting with the PZT).

3.2 Stators and Rotors

In either case, whether utilizing membraned wafers or thinned wafers, there are a variety of possible geometries for patterning the top electrodes for inducing traveling waves. Figure 7 shows the simplest layout for a rotary motor. Eight electrodes are patterned radially around a center point and driven four-phase over two wavelengths. Eight probes would be needed to drive the motor in this particular example. However, other patterns on our test wafer use an interconnect scheme between pads to reduce the requirement to four probes. Note in figure 7 that there are four extra pads. These can be used as sensors, since the piezoelectric film also is reciprocal, where a bending moment can induce a voltage.

The simplest way to observe electrical to mechanical energy conversion is to place a small object down on the stator as portrayed in figure 8. We have found that glass lenses spin the best, although dust particles dance wildly, signaling the onset of resonance as drive frequencies are swept from 50kHz through several hundred kilohertz. Typical rotational velocities of the glass lens are on the

Figure 6: This scanning electron micrograph shows a cross section of the nitride membrane structure with PZT and the gold top electrode. The titanium-platinum bottom electrode is too thin to see here.

order of 100–300*rpm*. One interesting point to note is that four phases are not necessary to induce spinning. In fact, the lenses rotate with only single pad excitation. This is likely due to wave reflections off the edges of the membranes setting up parasitic traveling waves.

In addition to rotary stators, we have fabricated linear stators as shown in figure ??. These structures can also be used as surface acoustic wave devices for measuring various properties of the ferroelectric film, such as acoustic velocity, etc.

3.3 The Process

Nitride membranes are first fabricated using standard bulk micromachining techniques into two-inch silicon <100> wafers. A 1-μm thick low-stress chemical vapor deposition silicon-rich (nonstoichiometric) nitride film acts both as the membrane and the mask for the tetra methyl ammonium hydroxide (TMAH) anisotropic silicon etch. The electroded PZT film (for the stators) is then formed on the membranes. The reduced stiffness of the membranes permit larger stator deflections than would be possible on a full thickness wafer.

Electrode material selection is critical to fully utilize the PZT properties. We have used a 0.46-μm thick platinum layer for our bottom electrode which is deposited on top of a 20-nm titanium adhesion layer. The nitride layer together with the titanium-platinum layers act as a separation barrier preventing the silicon from reacting with the PZT.

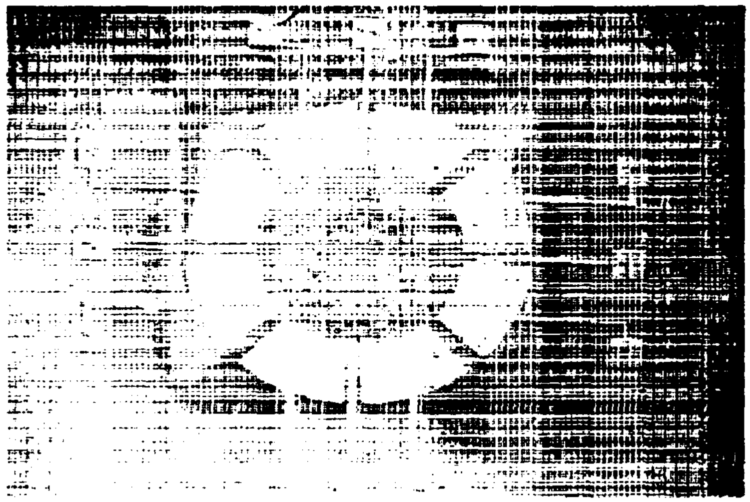

Figure 7: This 8-pole stator has an inner diameter of 1.2-*mm* and an outer diameter of 2-*mm* placed over a 2.2-*mm* by 2.2-*mm* square membrane. The eight pads are driven in a four phase sequence (sin, cos, -sin and -cos), repeated twice. The extra four pads at the north, east, south and west positions are undriven pads which can be used as passive piezoelectric sensors. That is, a signal will be generated as the wave passes through the pad.

Sol-gel PZT film is deposited by a spin-on technique in a series of steps. These films have been characterized as reported in [**Udayakumar et al. 91**] and show some significant improvements over bulk PZT, including a greater breakdown strength and dielectric constant. Although thin-film PZT was first developed for memory devices, much of that work has focused on sputtering and chemical vapor deposition methods, even though it is very difficult to get correct the PZT makeup with these techniques. Sputtering from three separate targets (or even from a single ceramic PZT target) to get lead, zirconium and titanium atoms all in their proper atomic positions in the crystal lattice is significantly harder than preparing a slurry of the proper composition and spinning it onto a wafer as in a sol-gel process. These sol-gel fabricated films do in fact, exhibit the proper perovskite structure and show strong ferroelectric characteristics. For memory applications, piezoelectric flexing is not of interest, but the conformal coating properties of vapor deposited films are. Sol-gel films on the other hand, are planarizing, which can be a problem where uniform thicknesses even over undulating surfaces are required. One critical requirement for preparing quality

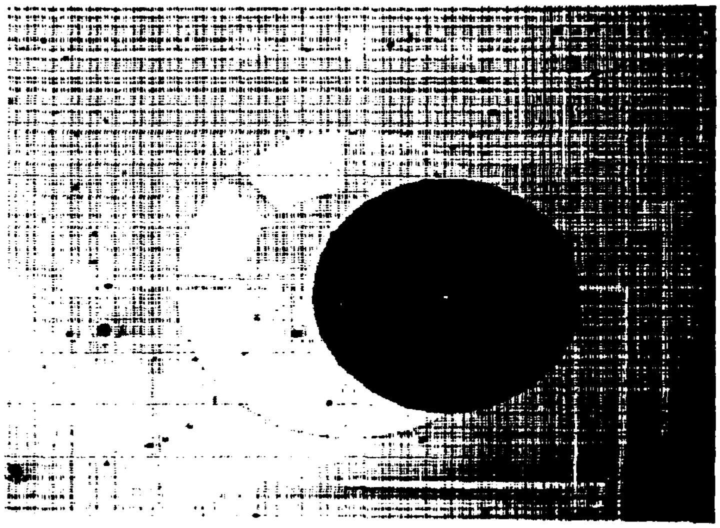

Figure 8: Here a plano-convex 1.5-mm diameter glass lens is placed convex surface down upon a rotary stator which has the same dimensions as figure 7. Although there is no bearing, the lens spins at 100–300rpm when the stator is driven at 90kHz.

sol-gel films is cleanliness, as wet spin-on techniques are more susceptible to the particle contamination than vacuum-based methods.

The sol mixture is prepared from the lead precursor, lead acetate trihydrate, together with alkoxides of Ti and Zr in 2-methoxyethanol as the solvent. Films are spun-on in approximately 50-nm layers. The film is pyrolyzed under quartz lamps after each step to remove organics. After 6-8 layers, the film is annealed to crystallize into the perovskite phase, which is the type of crystalline form which brings out the strong ferroelectric and piezoelectric traits. Annealing is carried out above 500C. These PZT films are of the 52-48 mole ratio of zirconium-titanium which places them on the morphotropic phase boundary. The morphotropic phase boundary is that composition for which the crystallites have the maximum number of possible domain states because the composition lies at the boundary of the tetragonal phase (6 possible domain states) and the rhombohedral phase (8 possible domain states). This position among the possible spectrum of compositions in the lead zirconate - lead titanate solid solution system is the most amenable for attaining the distinctive ferroelectric properties. One interesting point about these thin films of PZT, in contrast to its bulk form, is that poling, the process of aligning domains in order to bring out these

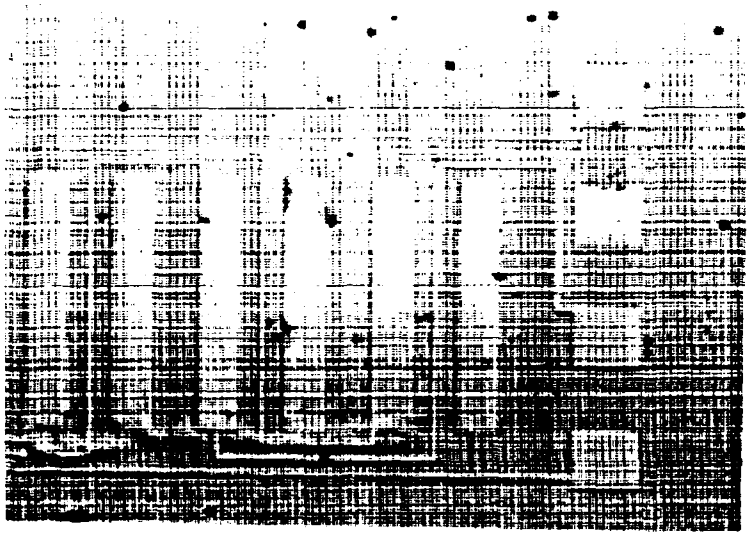

Figure 9: Linear stators have also been fabricated. Here, the probe pads to the right are 200-μm square and connect to every fourth electrode for setting up four-phase traveling waves. These structures are patterned over similarly shaped linear membranes.

strong ferroelectric characteristics, needs no longer be performed at elevated temperatures.

Characteristic measurements, described in more detail in [**Udayakumar et al. 91**] are summarized in Table I. Similar measurements reported in the literature for bulk PZT [**Jaffe, Cook and Jaffe 71**] yield some interesting comparisons. The breakdown field strength $1\frac{MV}{cm}$ is significantly improved over bulk PZT which is often on the order of $40\frac{kV}{cm}$. Our sol-gel PZT films also exhibit almost twice the relative dielectric constant, 1300, of (similarly undoped) bulk PZT which is 730.

Table I. Sol-gel PZT Film Characteristics

E_{bd}	$1\frac{MV}{cm}$	Breakdown field.
ϵ_{pzt}	$1300\epsilon_o$	Dielectric constant.
$\tan\delta$	0.03	Loss tangent
d_{33}	$220\frac{pC}{V}$	Long. piezoelectric coeff.
d_{31}	$-88.7\frac{pC}{V}$	Trans. piezoelectric coeff.

P_r	$36\frac{\mu C}{cm^2}$	Remanent polarization
k_{33}	0.49	Long. coupling factor
k_{31}	0.22	Trans. coupling factor
k_p	0.32	Planar coupling factor

Once the PZT film has been annealed, 0.5-μm thick gold electrodes are deposited and patterned by lift-off. A variety of eight- and twelve-pole rotary stators on three sizes of square membranes (0.8-mm, 2.2-mm and 5-mm per side) and various configurations of linear stators are patterned.

The structures built on thinned wafers are fabricated in an analogous manner except that the membrane etch is skipped and 0.5-μm oxide is used in place of nitride. The oxide layer together with the titanium-platinum layer act as a separation barrier preventing the silicon from reacting with the PZT.

4 Results

Initial experiments with these thin film PZT actuators have raised some intriguing questions. On the one hand, we have observed phenomena we expected such as high energy densities, gear down and low voltage operation. A $4V$ peak-to-peak drive signal at $90kHz$ competently spins a fairly large rotor, a glass lens 1.5-mm in diameter, at 100–300rpm. On the other hand, the lens spins competently with only one phase excitation, and does not spin any better with four, something we did not expect! Furthermore, changing directions when applying four-phase drive does not cause the rotor to reverse, although in one instance, it did cause the lens to stop. Essentially, we are not inducing traveling waves in the manner we would like, but evidently there is enough energy density that the lenses spin anyway.

We have observed other indications of high energy density. Not only do dust and particles vibrate across the stators upon resonance, but in certain instances in which a pad's impedance is very low, applying a voltage on the order of $10V$ will cause a static deflection dependent on voltage that can be seen through the microscope as a darkened area where the surface is deformed and reflecting light away from the eyepiece. An example with a unique stress pattern is shown in figure ??. Note that even at $10V$, the electric fields that we can apply across our 0.3-μm thick films contribute to energy densities well beyond those achievable with bulk ceramic PZT motors.

The single phase drive is intriguing and brings into question the effects of the boundary conditions on the waves imposed by the edges of the membranes. At high enough frequencies (several hundred kHz) standing waves become visible on both linear and square membranes. Rotors continue to spin however, even

Figure 10: Static deflection of this partially shorted stator pad can be seen through the microscope. The darkened portion is deformed, deflecting light away from the eyepiece. $10V$ are applied from the electrode at the right across the PZT, to the ground plane beneath it.

though the motors are not working in the manner in which they were designed. The plano-convex glass lenses seem to spin because the contact is a point. We have observed glass lenses, convex side down, jiggling across the stator until brushing up against the inner radius of the gold electrodes which are approximately $0.5\text{-}\mu m$ tall, whereupon they sit and spin. We have also observed that plano-convex lenses flat side down do not spin, nor do annularly shaped objects such as jeweled bearings.

In this first fabrication sequence, we made no attempt to microfabricate a bearing or etch a rotor in place. Consequently, the amount of frictional coupling is only determined by the weight of the rotor. In fact, it is possible there is no frictional coupling and the lens is merely sliding on air as the surface vibrates. Nevertheless, a mass is spinning and it is possible to calculate a torque by measuring the inertia of the lens and its acceleration when starting. Approximating our lens as a disk $1\text{-}mm$ thick and estimating from visual oservation that it reaches a final velocity of $3Hz$ in a quarter of a second, the resulting torque is $41\text{-}pNm$. We can compare to variable-capacitance electrostatic micromotors by normalizing over voltage squared, which gives a figure of merit over a class of experiments. This normalized net torque for such electrostatic micromotors (typically run at $100V$) is $1.4 \times 10^{-15} \frac{Nm}{V^2}$. The figure of merit for our piezo-

electric motors then becomes, for $5V$ excitation, $1.6 \times 10^{-12}\frac{Nm}{V^2}$, about three orders of magnitude larger. What this number actually signifies for a piezoelectric motor with no bearing and no traveling wave drive is debatable. Mostly, it serves to underscore that the films are indeed very active, encapsulate high energy densities and can move fairly large objects with low voltages.

True motor action will depend on future attempts to fabricate a bearing and to measure torques across a spectrum of normal forces. Further experiments are needed to determine better structures for guiding traveling waves. Instruments need to be developed for visualizing the waves throughout a spectrum of frequencies and for ascertaining the amplitudes of these dynamic deflections. Determining proper rotor-stator interface coatings for high friction contact would also be helpful.

Electrostatic motors are essentially the duals of magnetostatic motors which have been around for years and are well understood. Piezoelectric ultrasonic motors on the other hand are fairly new and ferroelectric thin films are newer still. Many factors conspire to produce complexities and difficulties in analyzing these structures: non-linear materials, coupled electrical and mechanical fields, resonance drives, clamped and unclamped waveguide boundary conditions and friction based interactions between rotors and stators, to name a few. Building mass-producible useful-torque-producing micromotors will be hard. Building complete gnat robots will be much harder. But the payoff will be enormous.

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